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Trumpet Augmentation and Technological Symbiosis

Abstract: This article discusses the augmentation of acoustic musical instruments, with a focus on trumpet augmentation. Augmented instruments are acoustic instruments onto which sensors have been mounted in order to provide extra sonic control variables. Trumpets make ideal candidates for augmentation because they have spare physical space on which to mount electronics and spare performer "bandwidth" with which to interact with the augmentations.

In this article, underlying concepts of augmented instrument design are discussed along with a review and discussion of twelve existing augmented trumpets and five projects related to mouthpiece augmentation. Common aspects to many of these examples are identified, such as the prevalence of idiosyncratic designs, the use of buttons placed at or near the left-hand playing position, and the focus on measuring or mimicking trumpet valves. Three existing approaches to valve sensing are compared, and a novel method for sensing valve position, based on linear variable differential transformers, is introduced. Based on the review and comparison, we created an example augmented trumpet that tests the feasibility of a modular design paradigm.

The results of this review of the state-of-the-art and our own research suggests future directions towards a better understanding of augmented trumpet design.

Introduction

There are musicians and instrument-builders in the world who are not satisfied with the limitations of acoustic instruments, bound as they are by their physical characteristics. The existence of *augmented* instruments as a field of study states this point quite clearly. Augmenting an acoustic instrument through the attachment of electronics expands its identity as a controller and producer of sound without discarding the years of practice that a performer may already have invested in his or her instrument. Augmented instruments are, therefore, a fascinating intersection between traditional technique and modern technology.

Many different types of acoustic instruments have been augmented, each posing different challenges in design and construction. Trumpets are particularly good candidates for augmentation owing, in large part, to the player's "spare bandwidth" (Cook 2001)—that is to say, the parts of the body that are unoccupied by performing the instrument. The left hand does not critically affect performance and can be used to interact with sensors instead of just supporting the weight of the instrument. Furthermore, there are no linkages or other delicate mechanisms to consider when attaching augmentations to a trumpet.

Although augmented trumpet designs have indeed expanded the scope of sound control available in performance, they have historically had the drawback of being focused on the needs of one particular performer and therefore have not been widely publicized, much less standardized. This has led to the current state of the art, in which we appreciate the expressive potential of augmentation (why to augment) and we have only just begun to systematically address the practical details of augmentation (how to augment). If the task of designing and constructing augmented trumpets was easier, and if common types of augmentations were better understood, it would eventually accelerate development of the art and the technology.

Before going any further, we must be clear about our terminology. The term *augmented* in this article is defined as "the addition of several

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sensors, providing performers the ability to control extra sound or musical parameters" (Miranda and Wanderley 2006, p. 21). In his Master's thesis, Andrew McNaughton (2011, p. 7) elaborates on this definition:

> Other terms used in the description or even title of such instruments are extended, hybrid, hyper, meta, electro-acoustic, cyber and even virtual. Bowers and Archer (2005) discuss this nomenclature and the etymology of hyper and meta, and propose their own reactionary infra-instruments. Despite the various names given, they notice among these augmented instruments a number of "recurring themes, [such as] rich interactive capability . . . detailed performance measurement . . . engendering of complex music . . . and expressivity and virtuosity" (Bowers and Archer 2005, p. 6). While there are differences in these terms and the instruments to which they relate, these differences are outweighed by the similarity of intention. These instruments are significantly different, however, from alternate, alternative, or "gestural controllers" (Miranda and Wanderley 2006, p. 19) like the EVI, which might or might not be modelled on existing acoustic instruments, but either way do not produce their own sound.

We further define an augmented instrument as an interface comprising sensors that capture gestures for controlling digital effects and synthesis. A *sensor* is "a device that receives a stimulus and responds with an electrical signal" (Fraden 2004, p. 2). The term *gesture* is generally defined in this article as "any human action used to generate sounds" (Miranda and Wanderley 2006, p. 5). Further discussion of gestural definitions and theory is beyond the scope of this article.

In the rest of this article we will review and discuss several augmented trumpets and the technologies used in their design. We begin with a review of existing augmented trumpets and discuss augmented instrument design concepts. This is followed by a comparison of three existing valve-position sensing technologies and an introduction of another sensor for this task, the linear variable differential transformer. We then detail an example of our own design that tests the feasibility of a modular design approach with on-board synthesis. Finally, we present conclusions and directions for future work.

Review of Previous Developments

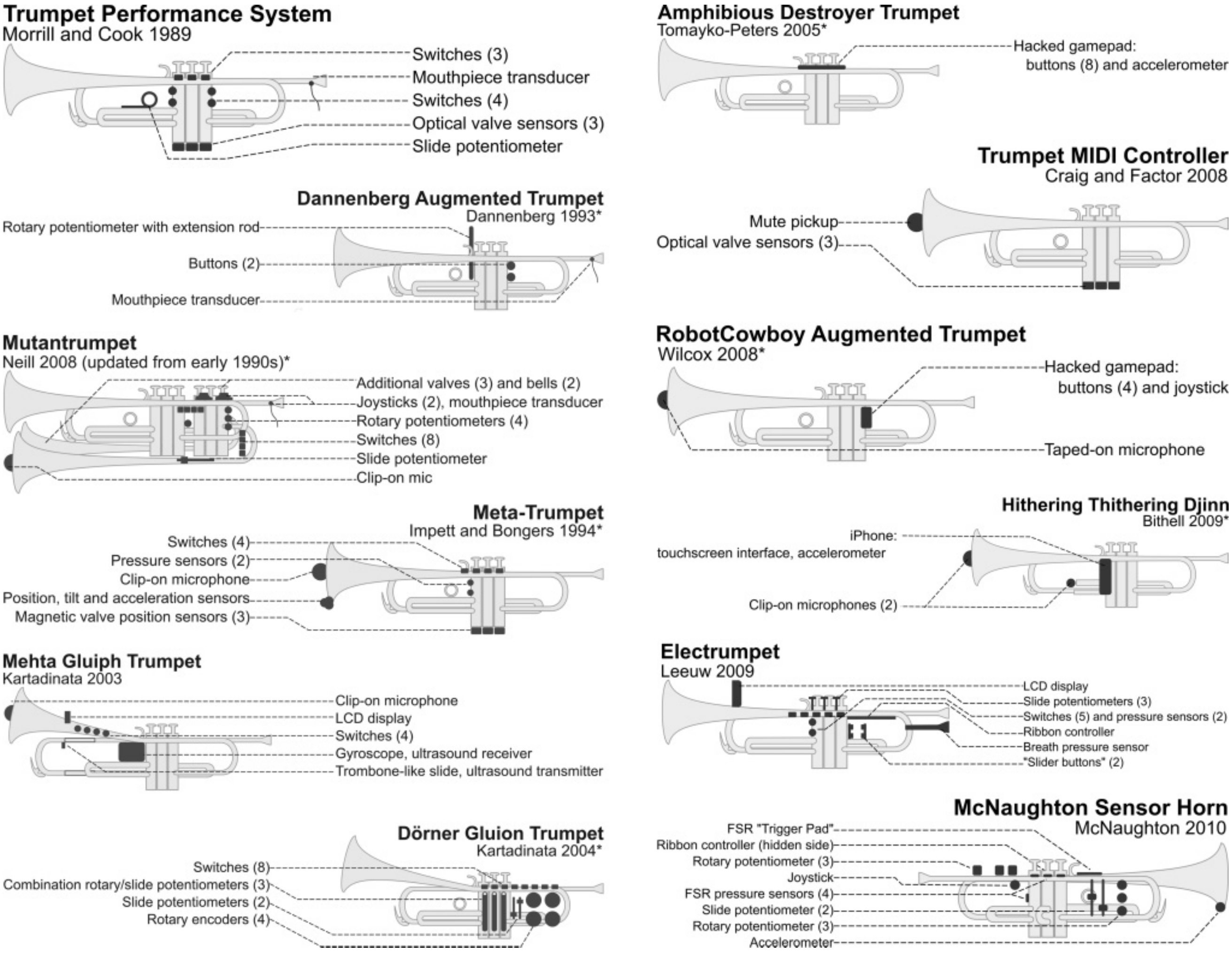
We know of twelve augmented trumpets that have been constructed over the years, as illustrated in Figure 1 (not counting our own design, described later). Many examples are documented in the literature, and several were found online. In those cases where previously published documentation left open questions, we contacted the original designer for additional details. Each implements a different set of augmentations, although there are notable commonalities.

We will look at these trumpets mainly in terms of the hardware elements used for gestural sensing, feedback, and signal processing while discussing related augmented instrument design concepts.

Gestures and Sensing

Augmenting an acoustic instrument places some limitations on the designer's palette of feasible gestures because of the performance gestures and existing mechanical interface which have been developed over centuries of acoustic practice. The traditional interactions between the performer and the trumpet are relatively straightforward. For example, a trumpet player will press on the mouthpiece of the trumpet with the lips and will press on the valves of the trumpet with the fingers of the right hand. Perhaps less obviously, a performer will tend to consistently move and sway his or her body and the instrument during performance (Wanderley et al. 2005). A fundamental question when augmenting an instrument is whether it should be playable in the existing way: To what degree, if any, will augmentation modify traditional techniques? The goal, according to our definition of "augmented," is to expand the gestural palette. Will this expansion come at a cost?

Figure 1. Illustrated comparison of existing augmented trumpets. Trumpets marked "" are included based on information found online and/or provided by the designers, and are labeled with their name and the year of invention (rather than a reference citation).*



For the most part, the existing works expand the gestural palette while preserving traditional trumpet technique. Hand-operated controls (such as potentiometers, buttons, and switches), familiar from many electronic instruments, are used in nearly every example and are clustered around the hand positions. This maintains the original hand positions as much as possible, while providing fast access to additional controls. Several examples do augment the existing mechanical interface elements, however, particularly the valves, and several mimic the traditional interactions on equivalent electronic interface elements.

An acoustic trumpet's fundamental physical connection to the player is between the player's lips and the mouthpiece. There have been several notable mouthpiece augmentations. Most of these sense the force applied by a trumpet player to the mouthpiece. Using strain gauges, Barbenel, Kenny, and Davies (1988) introduced a two-dimensional force transducer. Mayer and Bertsch (2005) extended this idea into three dimensions. More recently, Bianco et al. (2012) also used a strain gauge to measure one-dimensional force, whereas Democron and Leman used a load cell for the same task (personal communications with the authors). A project by

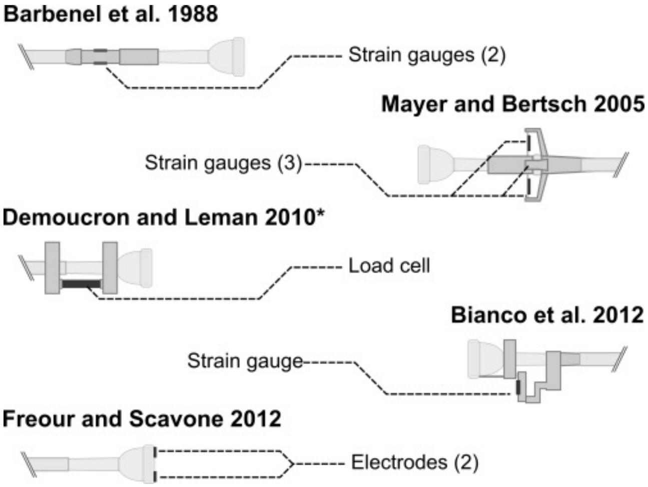


*Figure 2. Illustrated comparison of mouthpiece augmentations for trumpet-related research. These all measure force applied to the mouthpiece, with the exception of Freour and Scavone (2012), which measures lip oscillation. The example marked * is included based on information provided by the designer.*

Freour and Scavone (2012) used two electrodes to measure lip oscillations against a plastic mouthpiece, albeit for trombone. These works focused on measurements for acoustic and performance research. To our knowledge, no augmented trumpet has yet exploited lip pressure or oscillation for musical creation. The Electrumpet, however, includes an augmented mouthpiece alongside the acoustic mouthpiece, measuring breath pressure by means of a relative air pressure sensor (Leeuw 2009). These designs are illustrated in Figure 2.

The concept of valve augmentation was central to several designs seen here, either through direct measurement or valve-mimicking electronic controls. Axel Dörner (Kartadinata 2004) used hybrid (rotating and sliding) potentiometers—mounted alongside the acoustic valves—to capture his idiosyncratic acoustic technique of unscrewing the valve caps during performance. Ben Neill (2013) included a second set of acoustic valves to control airflow to the three acoustic bells on the Mutantrumpet. Hans Leeuw used slide potentiometers as "electronic valves" mounted alongside their acoustic counterparts. In a similar vein, Andrew McNaughton (2011) used three force-sensing resistors (FSRs) as "valve sensors" mounted alongside the acoustic valves. Three implementations included direct measurements of the acoustic valve positions. Cook, Morrill, and Smith (1992) used two optical switches per valve to detect four valve positions. Craig and Factor (2008) used a continuous optical sensor for each valve as a threshold detector, giving binary (up or down) positional information. Impett and Bongers glued shielded magnets to the bottom of the valve pistons—an intrusive but acoustically neutral augmentation—and continuously measured the resulting magnetic fields with Hall effect sensors underneath the valves (Impett 1994).

Augmenting the existing mechanical interface elements includes the potential to overload traditional techniques (analogous to the programming concept of function overloading). The additional layer of musical control gained through overloading can, in turn, modify the way that the instrument may be played acoustically. There are, of course, various degrees to which one may overload a technique. Some forms of technique overloading may only have negligible impact on acoustic playability, whereas others may entirely repurpose a given technique towards augmented musical control. It is a design choice to be understood and balanced with the musical aims of the instrument and the desired gestural palette. To illustrate the idea of overloading a gesture, consider Todd Machover's Hypercello (Machover 1992). In one mode of operation, the bow is divided into sections, each controlling the playback of a different recorded sound. The normal bowing technique is changed by this additional responsibility and the cello cannot be indiscriminately used as though it were purely acoustic.

All of the trumpets that involve valve measurement may include some degree of overloading, depending on how the valve measurements are applied. The Craig-Factor trumpet (Craig and Factor 2008) and Morrill-Cook trumpet (Morrill and Cook 1989) both use trumpet valve measurements purely for informing a pitch estimation algorithm—there is no effect on existing techniques.

There is at least one example of overloading a trumpet performance technique that expands sound control capabilities without significant disturbance of acoustic playability, and that is to simply measure the force applied to a valve near the end of its range of motion, illustrated in Figure 3. The Sensor Horn (McNaughton 2011) uses FSRs beside the trumpet valves as controls unrelated to the acoustic valves (except that they are manipulated in a similar

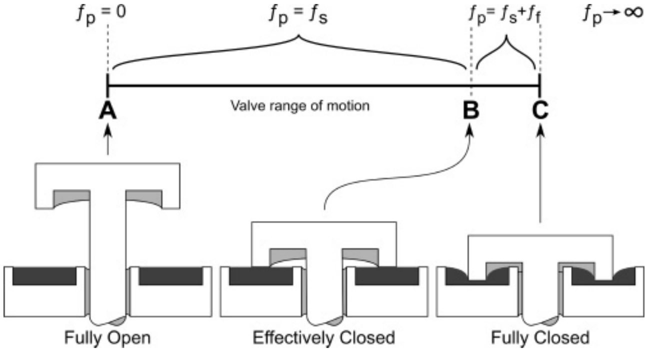


Figure 3. The force f_p *applied to the valve by the player is roughly equal to a combination of the force of the valve return spring* f_s *and the resistance of the felt padding* f_f *until the limit of the valve's range of motion, at which point the player may apply any amount of force without acoustic consequence. Therefore any force greater than that needed to effectively close the valve may be used as an "after-touch" parameter.*

Table 1. Trumpet Fingering Chart

Note	*000*	*010*	*100*	*110*	*011*	*101*	*111*	*001*
F♯3							●	
G3						●		
A♭3					●			
A3				●				○
B♭3			●					
B3		●						
C4	●							
C♯4							●	
D4						●		
E♭4					●			
E4				●				○
F4			●					
F♯4		●					○	
G4	●					○		
A♭4					●			
A4				●				○
B♭4			●				○	
B4		●				○		
C5	●				○			
C♯5				●			○	○
D5			●			○		
E♭5		●			○			
E5	●			○			○	○
F5			●			○		
F♯5		●			○		○	
G5	●			○		○		
A♭5			○		●		○	
A5		○		●		○		○
B♭5	○		●		○			
B5		●		○		○		
C6	●		○		○			

The column heading above a fingering shows the state of the three valves, with the binary number 000 indicating all valves open and 111 indicating all valves closed. The standard or most common fingering for a note is indicated by the ● character; ○ indicates alternate fingerings. Adapted with permission from Spang (1999).

manner). If the FSRs were mounted at the valve finger pads, pressure applied to the valve during valve manipulation could be used as an overloaded control. In such a way one could augment the trumpet with a sort of after-touch capability. This highlights the importance of identifying which performance gestures (or parts thereof) have an acoustic consequence.

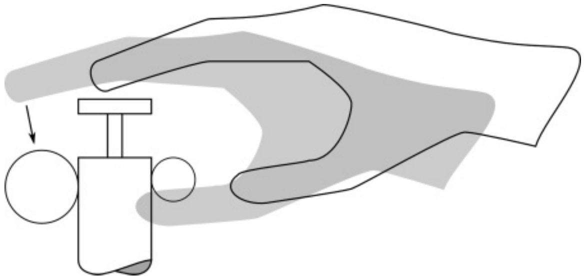
The use of nonstandard performance gestures can also be exploited for augmentation and is, thus, a form of technique overloading. These are performance gestures that are acoustically usable on the original instrument but are not normally used, for whatever reason (economy of motion, imperfection of tone, strength of tradition, etc.). On a trumpet there are several examples.

A trumpet can be de-tuned while playing to bend notes in a trombone-like manner. The Mehta Gluiph trumpet (Kartadinata 2003) incorporates a trombone-like slide and associated sensor in order to exaggerate and capture this nonstandard technique.

As previously mentioned, Kartadinata (2004) uses the nonstandard technique of unscrewing the valves during performance. This could be measured for use in sound control, perhaps with an optical sensor. Furthermore, removal of the valves after unscrewing them would be measurable with a valve-position sensor like those we have already seen.

Any trumpet with valve-position sensing can take advantage of nonstandard fingerings. Table 1 shows the notes produced by depressing different combinations of the valves. For example, to play an E5 (concert D5, given the most commonly used tuning of trumpets in B-flat), the trumpet player can use four different fingering positions (000, 110, 111, 001) of which one is the primary (000) and the other three being alternates. Alternate fingerings are not used in every register, but of particular interest is the fact that the third valve is never used on its own during normal trumpet performance. Admittedly, the traditional use of alternative fingerings—including the solitary third

Figure 4. Using nonstandard technique (shown in gray) to allow unobtrusive interaction with augmentations attached to the bell pipe.



valve—isn't unheard of, but for the purposes of augmentation it can be exploited with minimal obtrusion upon the playability of the instrument.

Trumpeters can press down the valves with the insides of their knuckles instead of the fingertips, as shown in Figure 4. This frees up the fingertips to interact simultaneously with augmentations such as switches or distance sensors mounted on the bell pipe of the trumpet. The Meta-Trumpet (Impett 1994) could be used this way. It has buttons mounted on the bell pipe alongside the valves, although the buttons are not explicitly intended for this technique. Similarly, the Mutantrumpet (Neill 2013) includes two joysticks just left of the rear set of valves that could be manipulated in this manner. The Sensor Horn's valve-adjacent FSRs could serve this purpose if one were to play the valves with the left hand instead of the right (McNaughton 2011).

Besides existing and nonstandard gestures there are, of course, those gestures that are normally not intended to produce sound—what Wanderley et al. 2005 refer to as "ancillary gestures"—or indeed ones that are designed "from scratch." Among the augmented trumpets seen here, there are some examples that exploit the position and kinematics of the instrument and player by measuring distance, velocity, acceleration, and rotation. The Meta-Trumpet (Impett 1994) uses ultrasonic distance sensors, accelerometers, and tilt switches to measure position, motion, and rotation, respectively, at the tip of the trumpet bell. The Amphibious Destroyer Trumpet (Tomayko-Peters 2006) and Hithering Thithering Djinn (Bithell 2009) both incorporate an accelerometer mounted near the valves. The Sensor Horn (McNaughton 2011) uses an accelerometer clipped to the bell (it could presumably be clipped to other parts of the instrument instead, or even to the player's right hand). The Mehta Gluiph Trumpet (Kartadinata 2003) has a gyroscope beside the bell to measure the instrument's rotational movement.

Feedback

Feedback is the visual, auditory, or tactile-kinesthetic mechanism by which a performer senses the state of his or her instrument (Miranda and Wanderley 2006, p. 11). An acoustic instrument inherently provides performance feedback to the player in the form of vibrations and perceivable instrument state. An electronic instrument, and for that matter electronic augmentations, needn't have any feedback mode at all except the sound produced (Tanaka 2000). Also, visual feedback can help the audience understand the instrument in performance, as exemplified in Gabriel Vigliensoni's SoundCatcher (Vigliensoni and Wanderley 2010). Among existing augmented trumpets there are three that use a feedback mechanism. The Mehta Gluiph Trumpet (Kartadinata 2003) uses a small LCD display mounted on the top of the bell, as does the Electrumpet (Leeuw 2009). Hans Leeuw has since switched to an iPhone for visual feedback, which is the same mechanism used in the Hithering Thithering Djinn (Bithell 2009), except that Bithell's iPhone is mounted on the left side of the valves to double as a touchscreen interface for sound control.

Signal Processing and Sound Generation

The sensor signals in an augmented trumpet must be processed before they are usable for controlling sound generation. All the augmented trumpets we have found incorporate hardware that collects and conditions sensor data. There are a variety of hardware platforms among these augmented trumpets, from general-purpose microcontrollers such as the Arduino used in the Electrumpet, field-progammable gate arrays (FPGAs) such as the Gluion used in the Doŕner Gluion Trumpet, and repurpopsed USB gamepads used in the Amphibious Destroyer Trumpet and the RobotCowboy Augmented Trumpet (Wilcox 2008). In terms of function there are few

Figure 5. Three trumpets we made. Top: An early test project with force sensors on the valve caps. Middle: A valve sensor comparison trumpet mounted in a wooden support structure. Bottom: Our modular proof-of-concept prototype, called Symbiote. In the first and last examples we used a Yamaha "Silent Brass" combined mute and pickup (not shown) to capture the instrument's sound.

differences. Every example discussed here acts as a sensor interface with sound generation and mapping outsourced to a PC or MIDI synthesizer. In most cases the communication with offboard hardware involves cabling the augmented trumpet sensor interface to the sound generator. Wireless communications and battery power, as used with the Electrumpet (Leeuw 2009), can help mitigate problems due to cabling but can also introduce problems of their own (Cook 2001).

Comparison of Valve Sensors

For a given gesture, there will be many possible sensing solutions, each with distinct advantages and disadvantages. Consider the desired level of detail in the measurement and the properties of the outgoing signal. Is it important to continually or completely measure a gesture? Are discrete steps or partial measures sufficient? After all, with clever conditioning and analysis a simple type of measurement can adequately represent a complicated gesture. There is a wealth of published information about the quantitative performance and general use of different types of sensors in print (e.g., Bongers 2000; Nyce 2004; Wilson 2005; Miranda and Wanderley 2006) and online (e.g., "Sensorwiki"; Wanderley et al. 2006) allowing instrument designers to more easily choose those that best fit their needs. In the case of valve-position sensing, augmented trumpets have taken, to date, different approaches to the level of detail. For instance, the Craig-Factor trumpet produces a binary threshold as output (Craig and Factor 2008), whereas the Morrill-Cook trumpet produces four positions (Cook et al. 1992). Other augmented trumpets (Bongers 2000; Leeuw 2009) provide continuous valve measurements.

We compared three of the valve-position sensors seen in previous examples: slide potentiometer, hall effect, and visible-red (as opposed to infrared) LED, to a fourth position sensor: the linear variable differential transformer (LVDT), to determine their suitability for different types of augmented trumpet projects (Thibodeau 2011).

The wooden support structure shown in Figure 5 held a trumpet and sensor chassis illustrated in Figure 6. We made a signal conditioning board for the LVDTs based on a design by Jean-Loup Florens for the ERGOS force-feedback device (ACROE 2013). Threaded rods were used to actuate the valves. The output signals of the set-up were sampled at 10 kHz by a National Instruments PCI-4472 capture card in a nearby desktop computer. The experimental trials focused on one valve (first valve—i.e., closest to the mouthpiece) with four sensors and a second valve (middle valve) with one sensor hooked up as a "marker," and progressed according to the following procedure:

1. Lower the actuation rod until it just touches the valve cap.
2. Start the data acquisition.
3. Position a digital caliper for measurement and zero its position to the valve position.
4. "Mark" the data point by pushing down the middle valve, then wait a moment to let the sensor signals stabilize (in case they were jarred by the movement of the valve).

Figure 6. Valve-sensing configuration. First valve is shown in cross-section at right.

Figure 7. Results of an experiment comparing different methods of tracking valve position. Notice the linearity of the potentiometer and linear variable differential transformer (LVDT).

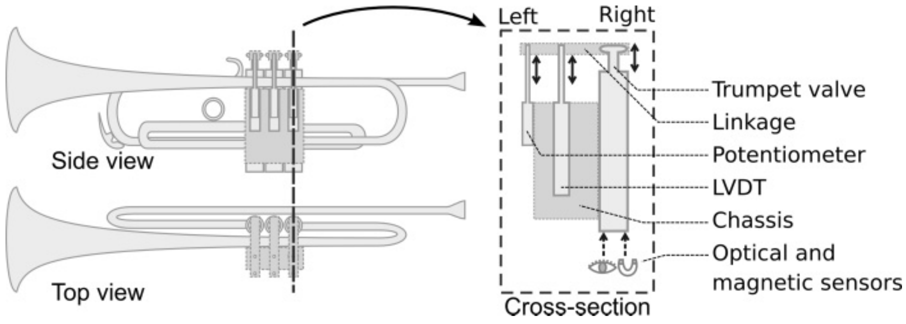


Figure 6

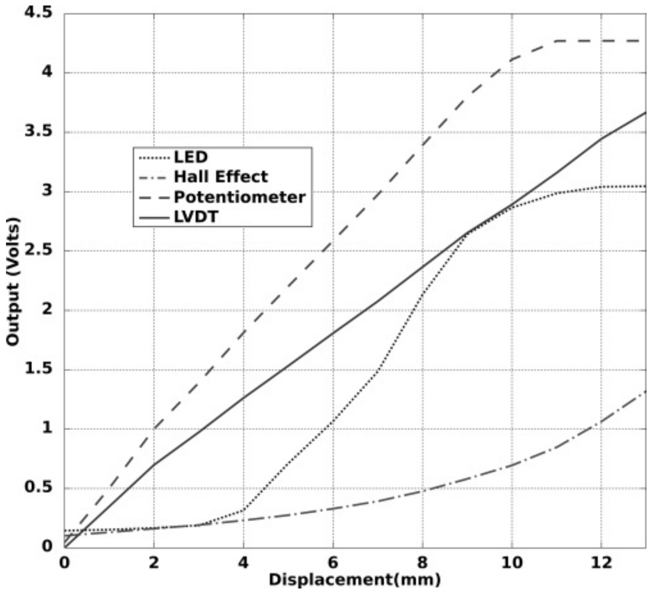


Figure 7

5. Lower the actuation rod until the caliper reads a displacement of 1 mm.
6. Repeat Steps 4 and 5 to generate all of the data points across the range of motion of the valve.

The quantitative results shown in Figure 7 show the advantage of the LVDT in terms of linearity and sensitivity.

Indeed, the LVDT is well known to have very linear, accurate, and repeatable characteristics (Nyce 2004), making it well suited for trumpet augmentation experiments requiring exact and reliable measurements (such as laboratory gesture analyses). The complexity of signal conditioning and the obtrusiveness of attaching the LVDT to the trumpet make it less than ideal for general use as a musical controller. The attachment mechanism in Figure 6 is heavy and bulky owing to the need to securely mount the LVDTs parallel to the valves on the far side of the bell pipe. It could be lightened by using a different material, but the bulk would remain an obstacle.

LED reflectance and Hall effect sensors, respectively, based on those used by Craig and Factor (2008) and Impett (1994) occupy the other end of the spectrum. As seen in Figure 7, the full-scale response curves of the these sensors are far from linear, although there is an almost linear segment in the response of the LED sensor. This nonlinearity is made up for by low weight, noncontact sensing, and ease of installation. These types of sensors are therefore well suited to performance environments where an exact linear measurement is not necessary for the practical control of musical parameters.

Note that the sensors involved in this experiment were approximations of their equivalents in the literature, not necessarily identical hardware. Our experiment compares technologies for valve-position sensing rather than comparing the efficacy of specific augmented trumpet designs against each other.

Symbiote

Electronic augmentations and the instrument to which they are attached form a kind of technological symbiosis. Thus, the inspiration for our own work in trumpet augmentation was the concept of a self-contained technological organism that lives, grows, and mutates as it expands the capabilities of its host and builds an aggregate identity: a *Symbiote*.

Based on the existing augmented trumpets, we built a proof-of-concept prototype to look at practical results stemming from our notions of standardization by modular design and on-board synthesis.

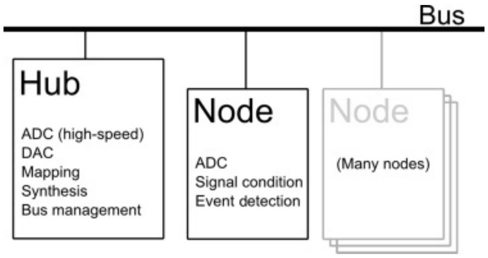
With the exception of the Trumpet MIDI Controller (Craig and Factor 2008), which was designed for trumpet players in general, existing augmented trumpets have been custom-designed for a particular performer or composition—tailored to an idiosyncratic performance style. A significant degree of technical skill is necessary to develop and maintain these instruments, limiting widespread access to (and experimentation with) augmentation technology.

This is not to say that customized implementations are undesirable. On the contrary, an augmented trumpet intended for performance by a specific artist should conform to that artist's idiosyncratic needs. The general needs common to all augmented trumpets (sensor interface[s], signal routing, parameter mapping, and sound synthesis), however, could be provided by a common design platform.

By standardizing the common elements of an augmented trumpet, development efforts could be dedicated to optimizing the instrument to match the performer. Furthermore, a *modular* augmented trumpet design platform would allow different designers to easily share and implement each other's ideas.

That said, there are obvious advantages to application-specific implementations. Above all, they use only the resources needed for the intended purpose (low overhead), allowing them to be optimized to their specific task (high performance). On the other hand, the inevitable need for maintenance and possible reconfiguration require the same technical expertise as needed for the initial construction, which can be viewed as a disadvantage. A modular system would ensure that parts could be replaced, if needed, and even reused, staving off obsolescence and minimizing electronic waste. Expanding in scope, a carefully designed modular system could make augmented trumpets accessible to performers who lack the technical expertise and resources to build an instrument from scratch. The fruits of a designer's labor would be available to a larger population who could in turn apply and expand upon augmentation ideas through musical and technological dialogue.

Figure 8. Architecture underlying the Symbiote design platform.



Conceptual Design

There are already many platforms on which to design musical controllers, such as the Gluion (Kartadinata 2006) and the now ubiquitous Arduino board. These are intended to acquire sensor data for mostly PC-based processing. Their acquisition infrastructure is limited by their number of analog inputs and outputs, and their architecture is not predisposed to on-the-fly hardware reconfiguration. In the case of the Gluion, the hardware is FPGA-based and therefore able to accommodate virtually any number of inputs/outputs but it is programmed with one specific configuration around which the rest of the instrument must be built. The Arduino has a limited number of analog inputs (the exact number depends on the model) and lacks built-in analog output. On the other hand, it provides an intuitive programming interface and is easy to set up.

The Symbiote aims to combine the advantages of the Gluion and Arduino platforms. Ideally, it represents a flexible and accessible system in terms of both hardware and software, and it has the power to perform sound synthesis on-board. Its design is based on modularity and distributed processing. A central module, the *hub*, connects to any number of peripheral *node* modules using a standardized communication infrastructure (see Figure 8).

Figure 9. Symbiote implementation and inset illustrated functionality. The hub is attached to the bell pipe, and the pitch estimator node is attached to the lead pipe (neither shown in inset). Fader and valve measurement nodes are attached to the valve assembly.

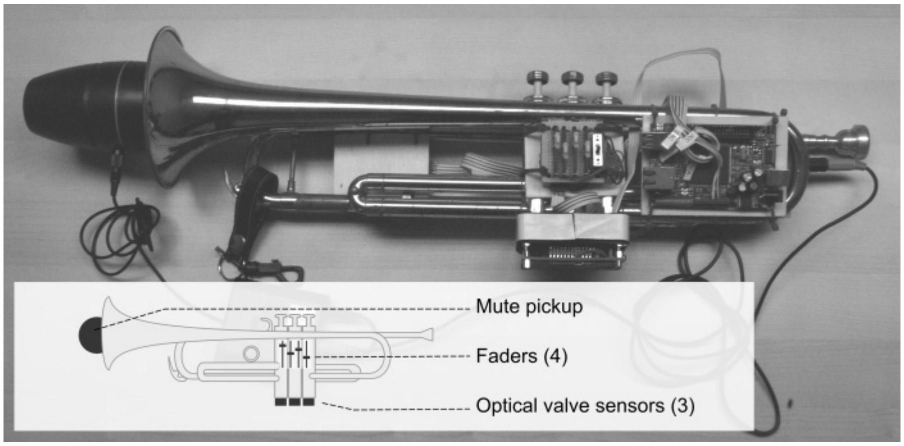


Figure 9

The hub is the "brains" of the Symbiote. It performs mapping and digital sound synthesis in addition to managing the nodes—providing bus addresses and subsequently pulling and pushing data as needed. It also performs analog conversion on necessarily high-speed inputs (such as audio inputs). An important function of the hub is direct communication with a PC for programming. The hardware used for the hub, whether an FPGA or microcontroller, must have significant processing power to perform digital sound synthesis.

A node can interface with sensors and displays, condition data, detect salient events, or perform specialized computing functions. It acts as an extension to the capabilities of the hub, but can be removed without disasterous consequences. A node only needs to be as powerful as is necessary for its task, and it uses a standardized physical connection to the hub for communications and power.

Bus networks are ideal for connecting an unknown or changing number of nodes. The communication lines are shared and therefore the number of connected nodes has a minimal impact on the hardware requirements. The disadvantage to a bus is that its throughput is limited by the number of nodes. The previously mentioned high-speed inputs on the hub handle signals that need to circumvent the limitations of the bus.

Figure 10. Symbiote implementation. See text for explanation.

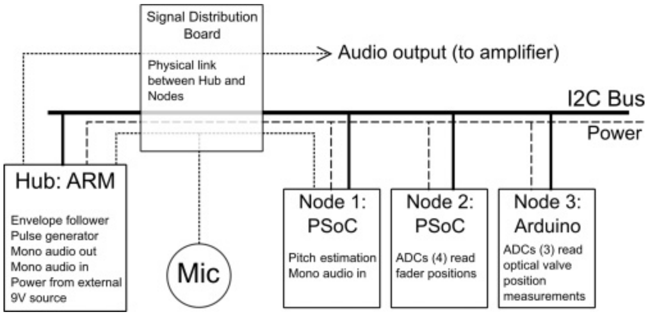


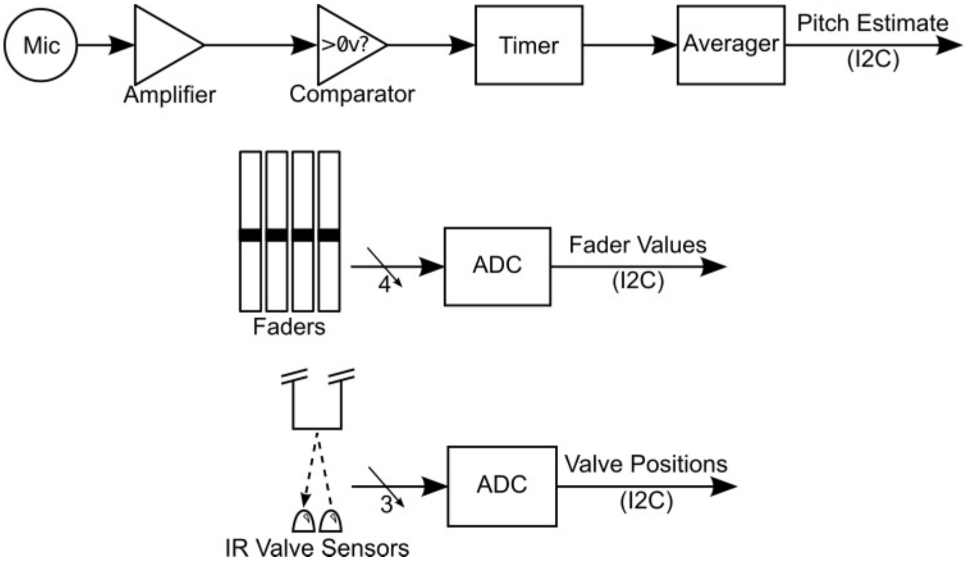
Figure 10

Implementation

We implemented the fundamental elements of the conceptual design (Hollinger, Thibodeau, and Wanderley 2010), shown in Figure 9. The goal was to test the idea that two standardized design elements—the bus communication protocol and the distributed processing architecture—could form a useful foundation for modular augmentation. There are four modules, a hub and three nodes, that are arranged as shown in Figure 10. Ribbon cables connect all of the circuit boards to power and bus signals. It is similar to the design used by Craig and Factor (2008) with embedded synthesis instead of MIDI output.

An inter-integrated circuit (I^2C) bus was the most attractive option for the communication system.

Figure 11. The three nodes: a pitch estimator based on the Programmable System-on-Chip (PSoC), a PSoC-based four-fader interface, and an Arduino-based interface to the valve-position sensors.



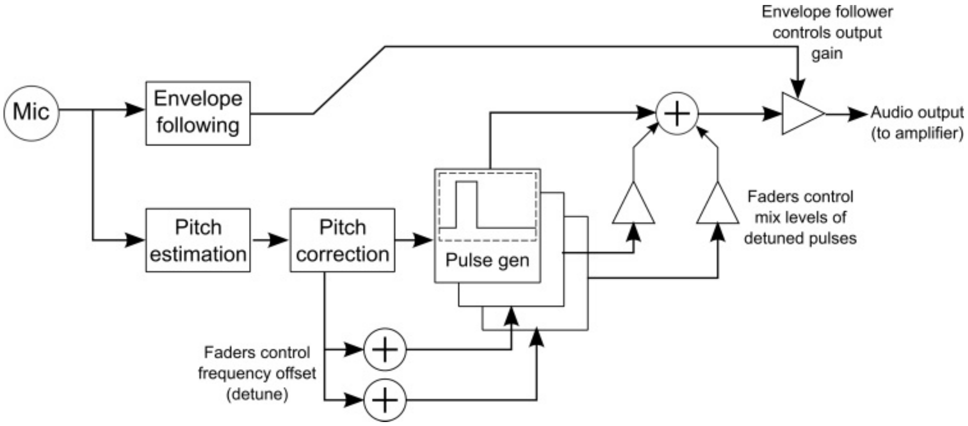
It needs only two wires (cutting down on physical bulk), it is simple to control, and it is implemented as a custom hardware block on many different embedded devices. It is not the fastest type of low-level bus communication but it is capable of serial communication speeds of up to 400 kbit/sec, which is fast enough for the control rates used in popular audio programming languages such as Pure Data. The nodes can be successfully connected to the hub at run time without needing previously defined I^2C addresses so that the hub "knows" at any given moment which nodes are connected and what each of them can do. This information is vital for mapping and synthesis.

The hub is an ARM development board. One of the hub's ADCs reads the microphone signal from the trumpet, from which it derives an amplitude envelope. On the software side, the hub manages I^2C communications and generates three pulse waves controlled in part by the outputs of the three nodes.

The lower computing demands on the nodes allowed us to choose less powerful devices in their implementations. Two of them are based on Cypress Semiconductor's Programmable System-on-Chip (PSoC), which have programmable analog and digital hardware blocks, thereby cutting down on peripheral circuitry and making them behave like a hybrid between a microcontroller and an FPGA. The Symbiote implementation shown in Figure 10 uses two PSoC-based nodes (one pitch tracker and one four-slider interface) and one Arduino-based node (valve sensing), detailed in Figure 11. Details of the signal processing are shown in Figure 12.

In operation, our prototype fulfilled its purpose, demonstrating the feasibility of a modular design platform with built-in synthesis. During the development process it was easy to isolate problems in the system, as the modularity made it very clear where a given problem originated, and any or all of the modules could be easily disconnected from the system (even while running) without catastrophic results. The project took longer than it would have if we had developed it as a fixed architecture, similar to the existing augmented trumpets. Nonetheless, the overhead of designing and implementing a modular architecture was a long-term investment. Once we had finished implementing the hub and one of the nodes, the other two nodes took very little time to complete because so many design elements were standardized across the system. The system has survived countless disassemblies and reassemblies, and to date it has never failed to operate in a live demonstration, which is as simple as powering it on and plugging the output into an amplifier.

Figure 12. Symbiote signal processing.



Conclusions and Future Work

There are numerous challenges in designing augmented trumpets and many questions about the effects of augmentation on the performer and their music.

It is clear from our review of existing projects that there are commonalities in the design and construction of augmented trumpets, for example, valve-position sensing, which we investigated by comparing four different sensing technologies including the LVDT.

Documenting the existing commonalities and commonalities that may emerge in future designs is essential to make the task of creating augmented instruments faster and easier.

Our experience developing Symbiote seems to indicate that a modular design platform would be ideal for projects that justify the initial overhead: long-term augmented trumpet projects with easily modifiable, expandable, and interchangeable parts.

There are necessary improvements to the Symbiote for it to grow from a proof-of-concept prototype to a performance-quality instrument. The hub's processing power must be upgraded to support more complex synthesis techniques. We are currently working on a version that integrates a Raspberry Pi development board running Pure Data as a more general on-board synthesis solution. A larger "palette" of nodes would allow for the kind of widespread modular experimentation that we envision. Integrating the on-board mapping and synthesis system with the Digital Orchestra Tools LibMapper (Malloch, Sinclair, and Wanderley 2009) via Open Sound Control would streamline the process of configuring the instrument. Finally, it would be extremely beneficial to foster an online community of trumpet augmenters, whether or not they adopt the Symbiote paradigm.

Trumpets, after hundreds of years of acoustic development, are growing beyond the limits of acoustic behavior. At present, an augmented trumpet is an acoustic trumpet with symbiotic electronics attached to it. It has been modified after the fact. There may come a time when an augmented trumpet is a refined instrument whose acoustic and electronic elements are manufactured together—and the term "augmented" may become irrelevant. The designers and performers of today's augmented trumpets are only just beginning to explore the potential of this instrument. Each one is an experiment and each experiment contributes to our understanding of how our technology shapes, reflects, and manifests artistic expression.

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